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Sensor less Control of PMSM with FOC using MRAS

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Abstract
Sensor less Control of PMSM with FOC using MRAS for speed estimation is implemented through Popov's Hyper stability criterion. The output of the adaptation mechanism MRAS is the estimated speed quantity using PI controller. The aim of the proposed sensorless control is to improve performance and robustness of PMSM drive under load and speed variations. The PMSM drive is tested for three different cases; with balance three phase supply, FOC and with MRAS using PI controller. The effectiveness and validity of the proposed control approach is verified by simulation results through MATLAB/Simulink/Sim Power System environment. It is found that the performance of the PMSM drive is better and also the torque, flux ripples are quite less with MRAS.

Keywords: *Permanent magnet synchronous motor (PMSM), Field oriented control (FOC), Model reference adaptive system (MRAS).*

Nomenclature

V_{ds}	direct axis stator voltage, V
V_{qs}	quadrature axis stator voltage, V
i_{ds}	direct axis stator current, A
i_{qs}	quadrature axis stator current, A
R_s	Stator armature resistance, Ω
p	no. of poles
L_{ds}	direct axis inductances, H
L_{qs}	quadrature axis inductances, H
λ_{ds}	direct axis flux linkage, wb
λ_{qs}	quadrature axis flux linkage, wb
λ_f	magnetic flux linkage, wb
ω_e	rotor speed in electrical, rpm
ω_m	mechanical speed, rad/s
J	moment of inertia, kg.m^2
B	Viscous Friction Co-efficient, Nm/rad/s
P	Differential operator
T_e	electromagnetic torque, Nm
T_L	load torque, Nm

1. Introduction
As PMSM Motor is made up of rare earth and neodymium boron magnets, it has been widely used in high performance variable speed industrial applications. In this motor, Permanent Magnets are placed in the rotor; because of absence of windings in the rotor; rotor copper losses are zero. Due to these advantages, this motor offers high effiency, high torque to inertia, high Power density [1]. PMSM are preferred in applications where it requires fast torque response and high performance operations [2] such as robotics, electrical vehicles, and servo applications [3, 4]. Both Permanent Magnet Synchronous Motor (PMSM) and Brushless DC motor (BLDCM) have permanent magnets on the rotor and require alternating stator currents to produce constant torque. But the torque ripples of the BLDCM are higher than that of the PMSM [1].

The scalar control is an open loop speed control method, doesn't provide a possibility to control the currents during various operation cycles like the start-up and loading conditions. The second method, vector control (FOC & DTC) is the most common method of speed control method for AC drives due to their dynamic response [5]. Comparison between FOC and DTC are based on various criteria including basic control characteristics, dynamic performance, and implementation complexity. The simulation and evaluation of both control strategies are performed using actual parameters of Permanent Magnet Synchronous Motor fed by an IGBT PWM inverter [6]. It presents a method of estimating simultaneously the motor speed and the rotor resistance of an induction motor by superimposing ac components on the field current command. The validity of the proposed method is verified by simulation and experimentation [7].
The structure and the control methods of PMSM are analyzed and simulation is realized using conventional direct torque control (DTC) method. It can be applied for PMSM and is reliable in a wide speed range applications [8]. Dynamic permanent magnet Flux Estimation of Permanent Magnet Synchronous Machines explains clearly about the rotor flux estimation in permanent magnet synchronous motor [9]. A Direct Torque

Controlled Interior Permanent Magnet Synchronous Motor Drive without a Speed Sensor has been presented with a speed control system for an IPM motor with an inner DTC which does not require a mechanical position sensor [10].
The problem of efficiency optimization in vector-controlled interior permanent magnet synchronous motor is investigated. It also describes a method for minimizing the losses in vector controlled interior permanent magnet synchronous motor drives [11]. A new control scheme for wide speed range operation of interior permanent magnet synchronous motor drives, where both torque and stator flux linkage are directly controlled is proposed in [12].It is proved that the dynamic performance of permanent magnet synchronous motor with vector control is better [13]. But the main advantage of DTC is that there is no requirement for transformation, and current regulator, but it gives high torque ripples [14]. The basic principle of DTC is to directly select stator voltage vectors according to difference between the actual & reference torque and stator flux linkages. In this paper along with stator resistance estimator is used [15]. In the DTC torque and flux ripples are high; to overcome this problem fuzzy controller is used. Using hysteresis band the torque ripples are reduced and MRAS technique is used for estimate the motor speed [16]. To trace the error between reference and actual values, the conventional controller PI, PID is implemented. To have better performance and accuracy in outputs, Model Reference Adaptive Control system MRAS is adapted [17]. The performance of the PMSM can further improved by implementing SVM control strategy along with DTC and Multi Level Inverters using Fuzzy Logic Controllers [18][19][20][21][22]. The hardware implementation of PMSM with PI Controller using FPGA is discussed in [23] using two level inverter with SVM control.
In this paper, Sensor less Control of PMSM with FOC using MRAS is implemented. The rotor speed is estimated using MRAS with PI controller. The paper is organized as follows: Section II revolves around the Field Oriented Control of Permanent Magnet Synchronous Motor. Section III explains the implementation of FOC for PMSM drive with the proposed MRAS.Section IV focuses on the simulation results for the dynamic performance of PMSM. Section V summarises the conclusions drawn from the work with future recommendations.

2. Field Oriented Control of Permanent Magnet Synchronous Motor

The principle idea of FOC is to introduce decoupling between field and torque producing component. This makes PMSM to behave like a separately excited DC motor. If the magnets are placed inside the rotor then $L_q > L_d$, otherwise if the magnets are placed on the surface of a rotor then $L_q = L_d$.
The modeling of PMSM motor in rotor reference frame is given from Eqns (1) to (8). The proposed block diagram of the work is given in Figure 1.

$$V_{qs} = R_s i_{qs} + P\lambda_{qs} + \omega_r \lambda_{ds} \quad (1)$$

$$V_{ds} = R_s i_{ds} + P\lambda_{ds} - \omega_r \lambda_{qs} \quad (2)$$

$$\lambda_{ds} = L_{ds} i_{ds} + \lambda_f \quad (3)$$

$$\lambda_{qs} = L_{qs} i_{qs} \quad (4)$$

$$v_{ds} = R_s i_{ds} + L_{ds}\frac{d}{dt} i_{ds} - L_{qs}\omega_r i_{qs} \quad (5)$$

$$v_{qs} = R_s i_{qs} + L_{qs}\frac{d}{dt} i_{qs} + L_{qs}\omega_r i_{ds} + \omega_r \lambda_f \quad (6)$$

$$T_e = \frac{3}{2}\frac{p}{2}\left[\left(L_{ds} - L_{qs}\right) i_{ds} i_{qs} + \lambda_f i_{qs}\right] \quad (7)$$

$$J\frac{d\omega_m}{dt} + B\omega_m + T_L = T_e \quad (8)$$

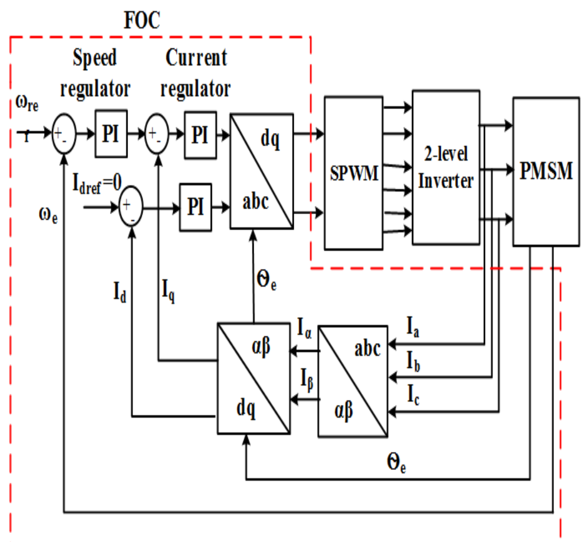

Figure 1. Block diagram of FOC of PMSM

3. Implementation of FOC for PMSM drive with the proposed MRAS using PI Controller

The Field Oriented Controlled electrical drives have rapid expansion in recent years. due to the achievements obtained in semiconductors for both power and signal electronics. This paper proposes to describe Field oriented control (FOC) of Permanent Magnet Synchronous motor (PMSM) using MRAS speed observer for sensor less control of drive.
This paper proposes a sensor less speed control based on MRAS, which is based on the comparison between outputs of two estimators. This estimated error is used to drive PMSM with a suitable adaptive mechanism to estimate the error speed. In this work MRAS is based on i_d, i_q of a PMSM, since FOC is used as a speed controller.
The general block diagram of MRAS is given in Figure 2.

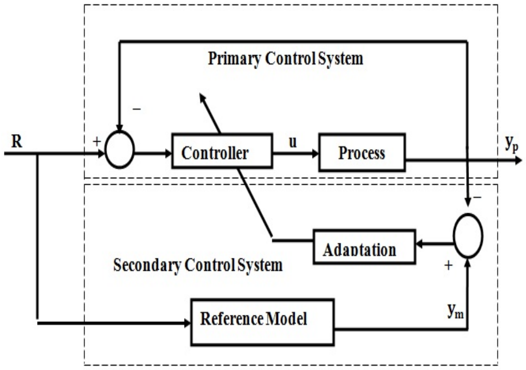

Figure 2.Block Diagram of MRAS

The main objective of MRAS is to estimate the rotor speed. Hence first i_d, i_q are represented in a state variable form is given by Eqn (9)

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e\frac{L_q}{L_d} \\ -\omega_e\frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} \\ \frac{v_q}{L_q} - \omega_e\frac{\lambda_f}{L_q} \end{bmatrix} \tag{9}$$

According to Eqn (9), the following Eqn (10) is derived

$$p\begin{bmatrix} i_d + \frac{\lambda_f}{L_d} \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e\frac{L_q}{L_d} \\ -\omega_e\frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix}\begin{bmatrix} i_d + \frac{\lambda_f}{L_d} \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} + \frac{R_s}{L_d^2}\lambda_f \\ \frac{v_q}{L_q} \end{bmatrix} \tag{10}$$

From Eqn (10) the reference currents and voltages are obtained as given in Eqn (11)

$$i_d^* = i_d + \frac{\lambda_f}{L_d},\ i_q^* = i_q,\ v_d^* = v_d + \frac{R_s}{L_d}\lambda_f,\ v_q^* = v_q \tag{11}$$

Using Eqn (11), Eqn (10) can be converted to Eqn (12)

$$p\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e\frac{L_q}{L_d} \\ -\omega_e\frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix}\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d}v_d^* \\ \frac{1}{L_q}v_q^* \end{bmatrix} \tag{12}$$

According to Eqn (12), the state equation of adjustable model of PMSM with speed angle as the adjustable parameter is represented in Eqn(13):

$$p\begin{bmatrix} \widehat{i_d^*} \\ \widehat{i_q^*} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \widehat{\omega_e} \\ -\widehat{\omega_e} & -\frac{R_s}{L_s} \end{bmatrix}\begin{bmatrix} \widehat{i_d^*} \\ \widehat{i_q^*} \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} \widehat{v_d^*} \\ \widehat{v_q^*} \end{bmatrix} \tag{13}$$

For SPM, L_d=L_q=L_s, so the adaptive speed mechanism can be simplified as follow:

$$\widehat{\omega_e} = \left(K_P + \frac{K_i}{p}\right)\left[i_d\widehat{i_q} - i_q\widehat{i_d} - \frac{\lambda_f}{L_s}\left(i_q - \widehat{i_q}\right)\right] + \widehat{\omega_e}(0) \tag{14}$$

Block Diagram of FOC of PMSM with MRAS is given in Figure 3.

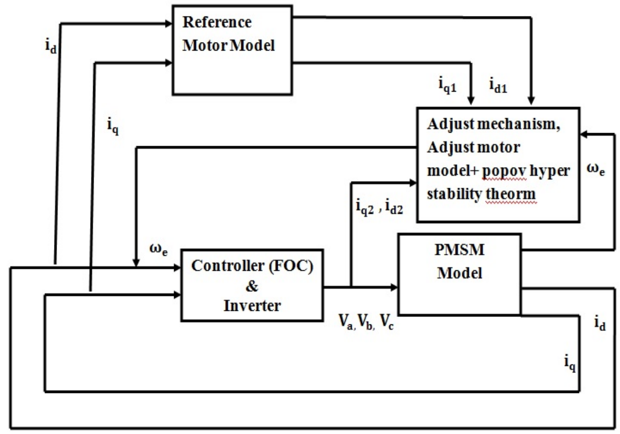

Figure 3. Block Diagram of FOC of PMSM with MRAS

4. Design of PI Controller - Conventional Controller

For process control in industrial automation the conventional PI controllers are extensively used because of its simple process, design, maintenance, economical, effectiveness, less number of parameter tuning and good performance for different operating conditions. Also it does not require the complete knowledge of the system. Hence these controllers are mostly preferred in industrial applications. [24] [25] [26]. The integral term in a PI controller causes the steady-state error to reduce to zero.

Speed controller plays an significant role in achieving aspiring dynamic characteristics of AC drives (PMSM). In this work, PI controller is considered in speed control loop [27] to investigate the dynamic response of a drive for different set speeds and load conditions. This is achievable by tuning the parameters of a PI controller, K_p and K_i [25].

The stability of a IPM and SPM drive system are analyzed as a linearized error model using PI controller. The general block diagram of the PI speed controller is shown in Figure 4..

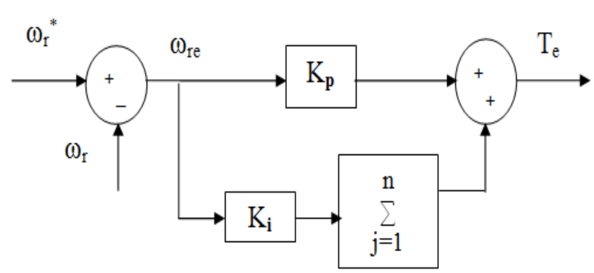

Figure 4 Block diagram of PI speed controller

The output of a speed controller (torque command) at *n*-th instant is expressed as follows:

$$T_{e(n)} = T_{e(n-1)} + K_p\,\omega_{re(n)} + K_i\,\omega_{re(n)} \tag{15}$$

Where $T_{e\,(n)}$ is the torque output of the controller at the n-th instant, K_p is the proportional gain constants and K_i is the integral gain constant. A limit of the torque command is imposed as

$$T_{e(n+1)} = \begin{cases} T_{e\max}, T_{e(n+1)} \geq T_{e\max} \\ -T_{e\max}, T_{e(n+1)} \leq -T_{e\max} \end{cases} \quad (16)$$

The gains of PI controller shown here are selected by trial and error method,

5. Results and Discussion

The dynamic performance of the PMSM drive is tested for three different cases as mentioned below:

i. Balanced Three Phase Supply
ii. FOC
iii. MRAS

i. Balanced Three Phase Supply

At first, the motor starts on no-load, after reaching to its rated speed of 1500rpm, a load torque of T_L= 2Nm is applied at t=0.1sec.

In the first case, the dynamic performance of PMSM Drive under balanced three phase supply is modelled in MATLAB/ Simulink/ Sim Power System environment. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms with three phase balance supply are plotted in Figure 5. In this case, there are lot of disturbances found in reaching steady state for speed and torque responses during starting. Whereas torque response has disturbance or lot of fluctuations when load is applied at t=0.1 sec. Response of torque and flux ripple waveforms with three phase balance supply are given in Figure 6. Since the input to the motor is a three phase balanced supply, it is observed that smooth response for torque and flux ripple waveforms as compared to the other two cases.

ii. FOC

In the second case, the dynamic performance of PMSM Drive with FOC is modeled. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms for rated speed are plotted in Figure 7.

In this case, there are few disturbances found in reaching steady state for speed and torque responses during starting as compared to the first case. Here the load torque T_L= 2Nm at t=0.1sec; T_L= 1.5Nm at t=0.4sec and T_L= 1Nm at t=0.5sec is applied and the dynamic performance of the drive is tested with rated constant speed 1500 rpm. Responses of torque and flux ripple waveforms with FOC for rated speed are given in Figure 8.

Also the drive performance is tested considering constant rated load torque of T_L= 2Nm is applied at t=0sec with varying speed from rated speed; 1500 rpm at t=0 sec; 1000rpm at t=0.1sec and 500 rpm at t=0.4sec. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms for rated load torque are plotted in Figure 9. Responses of torque and flux ripple waveforms with FOC for rated load torque are given in Figure 10. The torque and flux ripples are quite high as compared to the first case.

iii. MRAS

The same analysis is repeated for third case, the dynamic performance of PMSM Drive with MRAS is modelled. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms for rated speed with MRAS are plotted in Figure 11. Responses of torque and flux ripple waveforms with MRAS for rated speed are given in Figure 12. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms for rated load torque with MRAS are plotted in Figure 13. Responses of torque and flux ripple waveforms with FOC for rated load torque with MRAS are given in Figure 14.

It is found that the drive performance is better in terms of speed and torque wave forms and also the torque and flux ripples are quite low as compared to the FOC. The parameters used for PMSM is given in Table1.

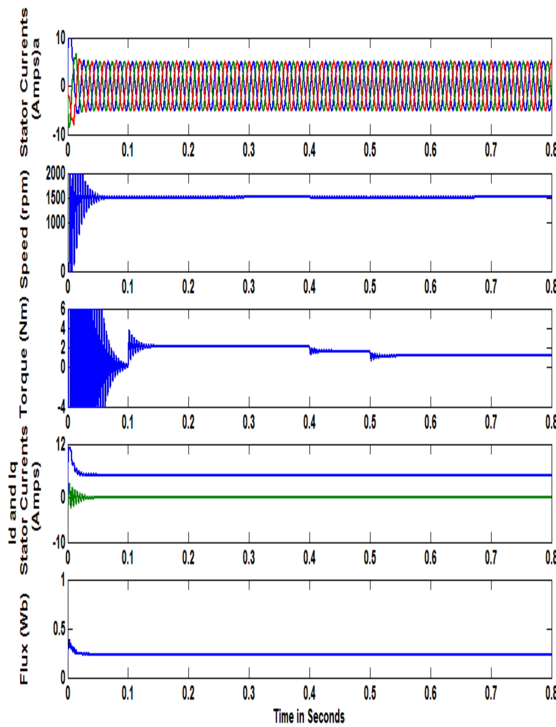

Figure 5. Response of Stator currents, speed, torque, direct current, quadrature current andflux waveforms with three phase balance supply

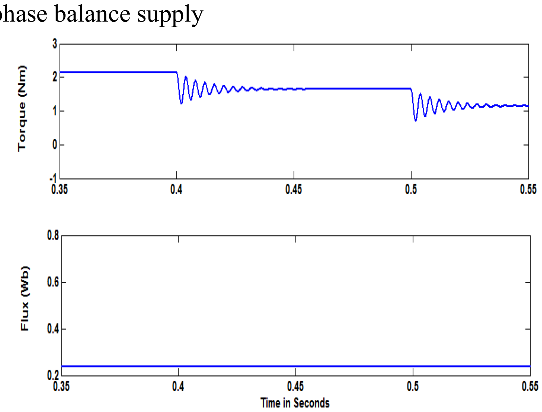

Figure 6. Response of torque and flux ripple waveforms with three phase balance supply

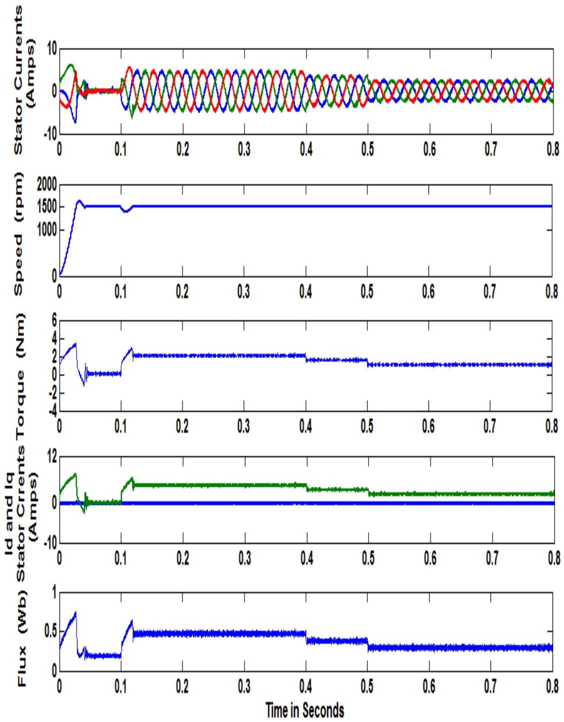

Figure 7. Response of Stator currents, speed, torque, direct current, quadrature current andflux waveforms with FOC for rated speed 1500 rpm

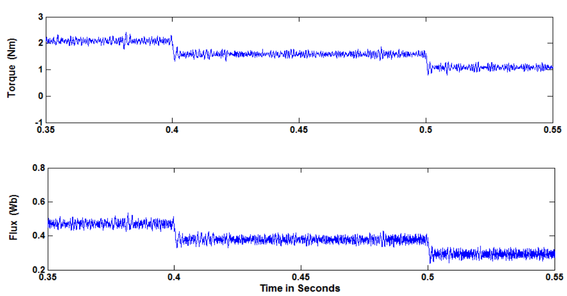

Figure 8. Responses of torque and flux ripple waveforms with FOC for rated speed .

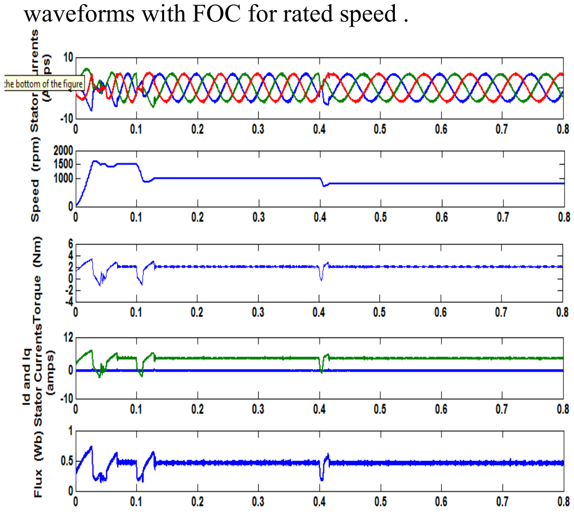

Figure 9. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms with FOC for rated load torque 2 Nm

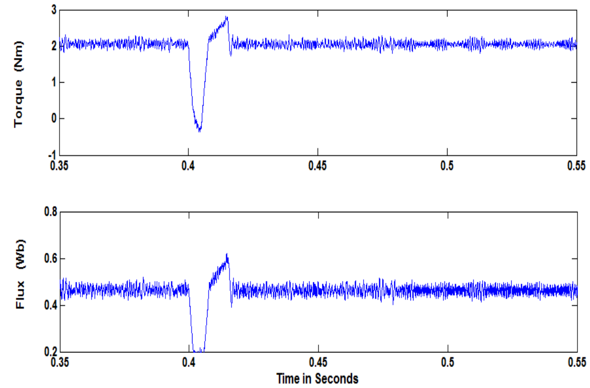

Figure 10.Responses of torque and flux ripple waveforms with FOC for rated load torque

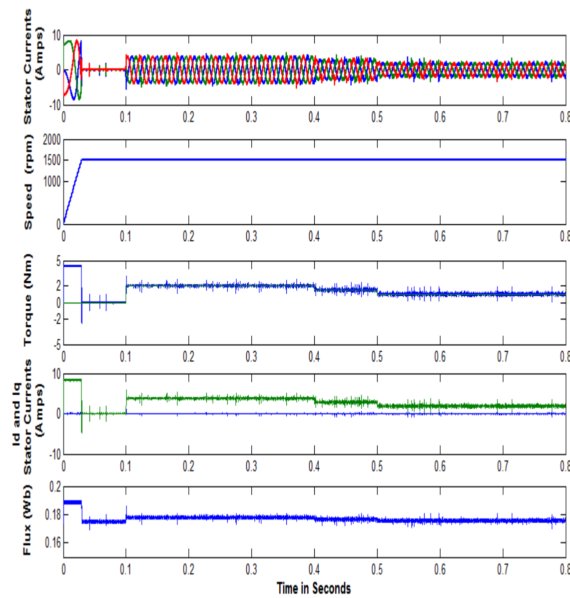

Figure 11.Response of Stator currents, speed, torque, direct current, quadrature current andflux waveforms with MRAS for rated speed 1500 rpm

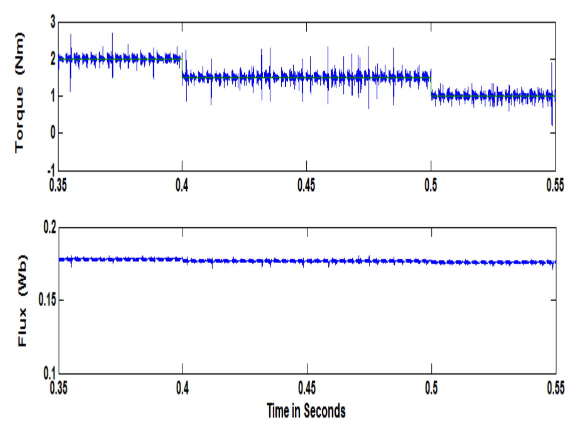

Figure 12. Figure 7. Responses of torque and flux ripple waveforms with FOC for rated speed .

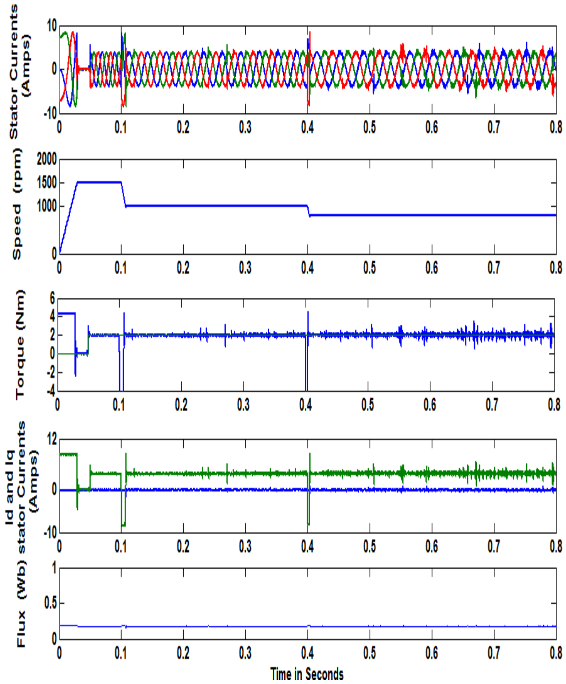

Figure 13. Response of Stator currents, speed, torque, direct current, quadrature current and flux waveforms with MRAS for rated load torque 2 Nm

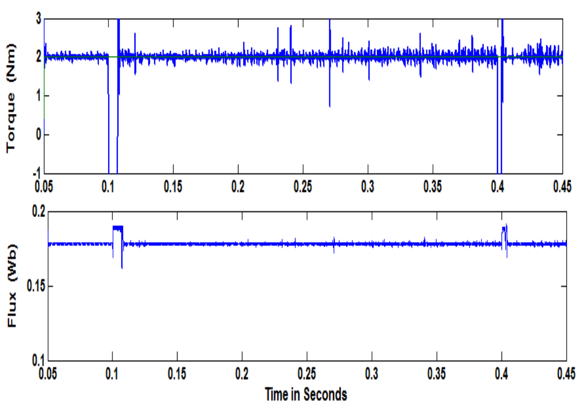

Figure 14.Responses of torque and flux ripple waveforms with MRAS for rated load torque

Table 1: Parameters of PMSM

Parameter Description	Value
DC Voltage (v_{dc})	230 V
Direct Axis Inductance(L_{ds})	0.075 H
Quadrature Axis Inductance (L_{qs})	0.095 H
Rotor Flux Constant (λ_f)	0.1540 Wb
Stator Resistance(R_s)	18 Ω
Number of Poles (p)	4
Moment of Inertia (J)	0.8111e3K gm^2
Viscous Friction Co-efficient (B)	0.0011 Nm/rad/s
Speed (N)	1500 rpm

6. Conclusion

Sensor less Control of PMSM with FOC using MRAS for speed estimation is carried out using MATLAB/ Simulink/Sim Power Systems is carried out in this paper. The output of the adaptation mechanism is the estimated speed quantity, which is used for the tuning in adjustable model and also for feedback. The stability of such closed loop estimator is achieved through Popov's Hyper stability criterion. The method is simple and requires less computation. The drive is tested for three cases and also for dynamic conditions. It is found that with MRAS with PI Controller, the drive performance is smooth and torque and flux ripples are less. Further this work can be extended with Fuzzy Logic Controller along Multilevel Inverter topology.It is further suggested that the proposed work further can be implemented with MRAS using fuzzy logic and FPGA Hardware implementation.

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